PWR GASIFIER PEER REVIEW REPORT
2/21/06

Background

Pratt and Whitney Rocketdyne (PWR) signed a cooperative agreement with DOE on 9/30/04 to develop a novel gasifier concept, which is expected to improve the availability and efficiency of gasification-based power plants, and to reduce plant capital and operations costs. On 12/21/05, PWR submitted a proposal to continue development of their gasifier into the next phase. On January 24, 2006, a peer review was performed to review the work that PWR has done to date, their technical approach for future development, and to assess the potential benefit of the PWR gasifier and feed system technologies over state-of-the art coal gasification. The peer reviewers also evaluated a DOE analysis of the PWR refractory, and a DOE system study comparing the performance and economics of the PWR gasifier to the GE and Shell gasifiers.

Because the cost of developing a new gasifier is likely to take a significant portion of the gasification program budget, it is imperative that any decision to continue development be based on the results of an objective and impartial evaluation of the information available. The peer review will provide the gasification technology manager with a professional assessment of the potential of the PWR gasifier, and the PWR and DOE project managers with guidance for improving technology development.

Additional background information can be found in the project Fact Sheet, and Development Overview, attached.

Executive Summary

Overall, PWR's proposal for follow-on work to continue the development of their gasifier and feed system met with mixed reviews. While it was felt that PWR had a strong technical staff who presented potential breakthrough concepts for improving the performance and economics of gasification, the development plan was considered too aggressive in being able to meet its milestones, and high risk because the sequences of activities key to risk mitigation were inadequate.

The novel concepts in the PWR proposal include development of:

- A gasifier based on rocket engine technology:
  - Multiple gasifier injectors, short residence time
  - Mechanically cooled, long life refractory liner
- An ultra-dense phase, high pressure, dry coal pump
- Uniform coal flow splitting in the feed system to support the multiple injectors

The PWR gasifier offers the potential for a 90% reduction in gasifier volume, which would reduce capital costs. A long-life liner would significantly improve availability,

and decrease operating costs. The ultra-dense feed pump will enable dry coal to be fed to a high pressure gasifier, resulting in increased gasifier efficiency at reduced gasifier volume, and reduced capital costs.

The ultra-dense phase coal pump, uniform flow splitting and mechanically cooled liner are concepts that, if successful, are likely to have a beneficial impact on the gasifier industry, regardless of the successful development of the PWR gasifier, because they could be adapted for use with other gasifiers. Also, it may be necessary for these relatively high risk concepts to be successfully developed for the overall PWR gasification technology to have significant merit over other state-of-the-art gasification processes. For these reasons, the peer reviewers recommend that the project continue along lines that ensure its development schedule adequately addresses the risks consistent with a viable commercialization pathway. Specifically, the peer reviewers recommendation is to continue support of the PWR gasifier technologies, if the development is separated into two phases to address these risks:

- Phase 1: Development of the ultra-dense phase coal pump, uniform flow splitting and mechanically cooled liner.
- Phase 2: Development of the PWR gasifier, contingent upon satisfactory testing in Phase 1 of the PWR feed system components critical for optimum gasifier operation.

The peer reviewers determined that the pilot plant part of the proposal and presentation did not adequately justify that the 18 tpd, 350 psi concept represented the optimum pilot plant design choice. The peer reviewers were unconvinced that the single injector, low pressure pilot plant was the best development path for demonstrating the PWR gasifier concept.

Two reports were not complete at the time of the review:

1. CANMET refractory coupon test results.
2. Economic portion of the Parsons system analysis.

The CANMET test results are likely to impact suggestions for further refractory development work, but are not likely to significantly impact the overall results of this peer review. The same cannot be said for the economic portion of the Parsons system analysis, since this will directly indicate the potential value of the PWR gasifier technology. Addendums to this report will be created when each of these reports has been considered by the peer review team, and the Executive Summary and Recommendations sections may be modified.

Peer Review Recommendations to DOE

1. Continue to support feed system development. Consider funding longer duration tests.
2. Continue to support mechanically cooled liner development, contingent upon an improved development test plan to:

    a. Take advantage of lower cost, smaller scale avenues.
    b. Consider alternative materials and systems that are less expensive and engineered for the application.
3. Delay pilot plant construction and operation until:
    a. The feed system design is proven viable through Phase 1 activities.
    b. PWR reconsiders and better justifies their pilot scale design.
4. Obtain reconciliation between the Parsons and PWR economic analysis results.
5. Perform a system sensitivity study to define the optimum operating pressure for a gasifier, with consideration of future downstream technologies and CO2 sequestration.

Discussion

Feed System

The discussion of the PWR high pressure, multiple injector feed system covered three main focus areas: 1) Risk, 2) Benefit to the PWR gasifier concept, and 3) Benefit to the gasification industry.

All of the peer reviewers concluded that long term, reliable operation of the coal pump and flow splitting process were among the highest risk concepts in PWR gasification technology. Although the PWR pump candidate concepts appeared to be well investigated theoretically, no physical tests have been done on the PWR feed pump concept. Concerns were raised about the safety of the planned 1,200 psi pump, since it is only inter-particle forces on the compressed coal that will maintain the pressure barrier. Furthermore, for the PWR gasifier to work at optimum efficiency, the multiple flow splitting process must be consistently uniform over long periods of time. Though PWR showed historical data of similar coal flow splitting processes, they were not identical processes, and the tests were of short duration.

The peer reviewers all believed that reliable operation of the feed system was critical for the PWR gasifier technology to succeed. Although PWR stated they were willing to move forward with lock hoppers, if necessary, this would result in a significantly lower gasifier pressure, and will probably have an attendant adverse effect on plant economics. No system studies prove that the PWR gasifier will be a benefit over state of the art gasifiers at a reduced pressure. Some reviewers believed that at the lower pressure, the PWR gasifier would not be a significant improvement over the Shell gasifier. The general consensus was that if it became necessary to run the PWR gasifier at a lower pressure, the viability of the PWR gasifier to demonstrate economic advantages was questionable. Before any continuance of the development of the gasifier under these circumstances, it was recommended that at a minimum a system study be performed to show its continued value. Regardless, uniform, consistent flow splitting is critical for acceptable performance of the PWR gasifier; no backup for this process was described.

Some reviewers discussed the possibility that the Stamet pump could be used by PWR so there was no need to develop another pump, while others questioned whether the Stamet pump would be ready for use in time to support PWR gasifier development. According to PWR, the PWR development plan would be significantly delayed if they had to wait for the Stamet pump to be developed to a useful scale. Also, PWR believes the use of the Stamet pump would increase the capital cost of their feed system to the point of significantly impacting what they want to provide as a PWR gasifier package cost. (Note: Technical comparison of the PWR pump concept to the Stamet pump is being performed under an RDS task, and will be presented to DOE separately.) It was outside the scope of this peer review to perform an in-depth comparison of the two pumps, or to consider the commercial ramification of having one dense phase coal pump available, or two.

There was general consensus among the reviewers that successful development of the PWR feed system would be a benefit to the gasification industry as a whole, since other gasifiers could use the system to improve their efficiency.

Peer reviewer consensus was to recommend that development of the PWR feed system move forward, and that the PWR feed system be proven before DOE considers any co-funding of the gasifier pilot plant. The serial order of development was recommended because the feed system was believed to be higher risk, is a critical component to achieve PWR's technologies advantages over present commercial systems, and development of it will cost less. Should this recommendation be accepted, it appears that this could delay the development of the overall PWR gasifier technology by up to three years.

Additional recommendation: duration of the feed system tests be increased, to prove that it can not only perform, but perform over a long life.

PWR Gasifier

The peer reviewers were generally impressed by the PWR multiple injector, plug flow, rocket-based gasifier concept, and believed development should be continued, once the feed system was proven to work reliably. The gasifier concept could represent a significant change and improvement over conventional systems.

The peer reviewers were concerned that the 1970 gasifier tests may not translate well from hydrogen to coal applications, and that the data provided was not complete. A major flaw was that there was no experimental mass balance based on this data. The spray quencher may represent a design enhancement, but several reviewers thought this could also represent more of a challenge than PWR acknowledged in their presentation because of the high pressure, small volume quench domain. However, the peer reviewers generally believed these problems could be resolved during development.

There was general dissatisfaction among the peer reviewers about the proposed 18 tpd pilot plant, which is the next proposed development step for the PWR gasifier. The over-

riding concern with the pilot plant is that its configuration, as proposed, will not provide an adequate database for scale-up to first commercial offering. The commercial PWR gasifier will have numerous injectors (nominally, 36) and to operate at 1,000 psi. The PWR pilot plant will have one injector, and will operate at approximately 350 psi. The lack of similarity between the commercial vision and the proposed pilot plant was a major concern to all of the reviewers. The lower pressure was of concern to most of the reviewers, because critical gasifier operation characteristics vary at different pressures.

Specific concerns with the PWR pilot plant are that the following would not be representative of the commercial-scale plant:

- Cold gas efficiency
- Carbon conversion
- Oxygen demand
- Spray quench
- Exit gas composition
- Gasifier heat losses
- Injector life
- Liner life
- Slag/ash characterization and removal
- Gasifier feed density may not be representative of the PWR ultra-dense feed system under development

It is believed that the PWR pilot plant would be useful to help resolve flame-out issues, injector plugging, mass balance verification, and some materials issues. However, it was not believed that a pilot plant was necessary to resolve the materials durability concerns. The major flaw in the proposed one injector, low pressure unit is that it would not be representative in terms of mixing efficiency, conversion, etc., and would be inadequate for a CFD model to use for scale-up designs. PWR did not adequately explain how data from the pilot plant would translate to their commercial vision.

There were mixed thoughts on what would be a better development step. It was determined that it was outside the scope of the peer review to form a specific recommendation, as that would require an in depth engineering analysis. Reviewers questioned if gasifier tests could be run at the University of North Dakota to demonstrate flow splitting and high pressure operations.

Recommendations:

- PWR must re-evaluate their pilot-scale gasifier design. The challenge is to design a small-scale plan that will more accurately predict commercial results. After re-evaluation, they must better justify the path proposed, and also discuss why alternate paths were rejected.
- DOE should perform a sensitivity analysis of an overall gasification-based system including technologies expected to be ready for commercial-scale demonstration by 2015, and CO2 sequestration, to determine optimum gasifier pressure. This is necessary for DOE to have a rational pressure target for gasifier development.

Refractory

The mechanically cooled refractory is another area, like the feed system, considered both high risk, and of potential benefit to other gasifier systems. Though the general opinion was that the concept could work, it was impossible to assess this on even a preliminary basis since the data from the CANMET tests was not available (due to delays in the testing). The CANMET tests will test mechanically cooled refractory coupons in a very small, slagging gasifier and will provide the first real opportunity to assess the performance of the ceramic composite in the presence of a flowing slag. The CANMET data will be evaluated later, and will be included as an addendum to this report. Preliminary thoughts on the PWR refractory development plan are:

- More testing should be done at bench-scale/CANMET in parallel development with the rest of the PWR gasifier development plan. The analysis done by NETL's Mary Anne Alvin should be used to improve the refractory development plan. These tests should include evaluation of system weaknesses, including potential problems with the gap behind the refractory. Also critical are the study of the impact of slag exposure on the integrity of the composite's fiber-matrix interface, since failure of this interface will result in large-scale spalling of the liner (and significant material loss), and the study of the effect of thermal cycling on the adherence of the slag to the ceramic surface.
- Less expensive materials should be considered as an alternative to the very expensive ceramic matrix composite. This will become much more important if the gasifier must operate at lower pressure, as the inner diameter of the gasifier will increase significantly.
- The proposed pilot-scale gasifier will provide useful information on the liner, but it won't simulate the commercial gasifier environment.

The peer reviewers recommend to continue development of the refractory, contingent upon an improved development plan. Consideration must be given to:

1. Less expensive, smaller scale tests prior to PWR pilot plant tests.
2. Less expensive materials

Feed System and Pilot Plant Integration

There was general discussion and concern about the split development plan: 1) The 400 tpd, 1,200 psi feed system, and 2) The 18 tpd, 350 psi gasifier. Individual suggestions were made for an integrated test system, or to increase the operating pressure of the proposed gasifier pilot plant. No consensus occurred, and no recommendations were made.

Overall PWR Concept

There was general agreement that if PWR's gasifier development plans succeed, there is potential for their gasifier to have lower capital cost, higher availability, and improved efficiency compared to current state-of-the-art gasifiers. It was also generally believed that PWR had a strong technical staff working on this project, and that most problems they would encounter could be resolved; however, all of the concepts must be successfully developed for the PWR gasifier to function as described. On the positive side, successful development of many of these concepts (feed pump, refractory, etc.) would be a significant benefit to the general gasification industry, even if the overall PWR technology was not a success.

Coming to a conclusion on the extent of the overall value of the PWR gasifier technology was difficult because the Parsons system analysis was not yet complete. The Parsons system analysis was supposed to compare the PWR gasifier efficiency, economics, etc. to the GE and Shell gasifier. The performance portion was complete in time to be part of the peer review, but the economic portion was not. Some of the preliminary economic information provided by Parsons varied significantly from PWR estimates. There was agreement among the peer reviewers that there needed to be reconciliation between the two views of the potential economic benefits of the PWR gasifier. Parsons will have additional discussions with PWR staff, prior to completing their system analysis. The final system analysis will be will be considered by the peer reviewers and an addendum to this report will be created.

Peer reviewer concerns that will not be resolved by reconciliation and completion of the system study analysis:

- The incremental improvements anticipated to the E-Gas and Shell designs will not be accounted for in the system analysis.
- The long term PWR development schedule does not address mitigating risks. Often, insufficient time was allotted in the schedule for operation information from a previous development stage to be used in a later stage.

Peer reviewer conclusions TBD, dependent upon the completed Parsons system analysis.

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